DYNAMIC COMPRESSION TESTING OF
CRUSHER GAGE MATERIAL

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DYNAMIC COMPRESSION TESTING OF CRUSHER GAGE MATERIAL

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ABSTRACT: In order to determine the validity of static
calibration of crusher gages, annealed copper crusher gage
material has been tested in compression at room temperature
at rates of strain from 1.66×10^{-3} in/in/sec to 7.15×10^3
in/in/sec. A modified Hopkinson bar apparatus as originally
used by Kolsky was used to obtain dynamic stress-strain
relations for this material. It has been found that this
material is weakly strain rate sensitive and static cali-
bration of crusher gages will introduce an insignificant
error in the measurement of dynamic peak pressures.

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DYNAMIC COMPRESSION TESTING OF CRUSHER GAGE MATERIAL

This report is part of the continuing effort of the U. S. Naval
Ordnance Laboratory in the determination of dynamic properties
of materials.

The author would like to express his appreciation to the many
individuals who assisted in this undertaking, especially
Mr. John Marshall for his assistance in conducting the
experiments and Mrs. Louise Brown for her assistance in
the reduction of data.

                          SAXE P. GANTZ
                          Captain, USN
                          Commander

                          a. e. Seigel
                          A. E. SEIGEL
                          By direction

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ILLUSTRATIONS

List of Symbols

a	Lagrangian coordinate
E	Young's modulus
g	"shift rate" defined by equation (2)
ℓ_o	original specimen length
t	time
u	particle velocity
ϵ	engineering strain defined as $\Delta\ell/\ell_o$
$\dot{\epsilon}$	strain rate defined by equation (4)
ρ	mass density
σ	engineering stress
ϕ	"impact velocity" defined by equation (3)

Subscripts

AVG	average value
I	incident pressure bar
M	measuring region in incident pressure bar
R	reflecting surface
T	transmitter pressure bar

INTRODUCTION

In the analysis of any structure, a careful examination of the loading time must be made. If the inertial forces in the structure are insignificant, a static analysis of the structure will be adequate. However, if the inertial forces are comparable to the internal forces, then a transient analysis must be undertaken which involves the propagation of stress-waves in the material.

In 1942, T. von Karman (reference 1) and G. I. Taylor (reference 2) independently developed a method to interpret and calculate elastic and plastic stress-wave propagation. This method is a one-dimensional analysis based on the equations of continuity and momentum. Since von Karman's and Taylor's work, numerous investigators have used this method in studies of wave propagation with satisfactory results. However, the use of this method requires extensive use of the stress-strain relation of the material. If the stress-strain relation is dependent upon the rate at which the specimen is loaded, then the material is said to be strain-rate sensitive. This sensitivity may cause extreme errors in predicted strains if the static relation is employed in the one-dimensional wave theory.

A typical example of how this effect may distort predicted results is the "crusher" gage. These gages employ a type of annealed copper in the form of spheres or cylinders to determine the peak pressures in situations where more fragile devices would fail. One use of these gages is in the high-pressure chamber of high performance guns where the gage is subjected to violent changes in pressure. The peak pressure is deduced from the permanent strain in the gage. Since these gages are calibrated statically, if the material responds differently when loaded dynamically than statically, an error in the apparent stress will result.

One method employed to determine this dynamic characteristic of materials is a modification of the Hopkinson pressure bar as used by Kolsky (reference 3), Chiddister and Malvern (reference 4) and Hauser, Simmons and Dorn (reference 5). The split Hopkinson bar technique permits the measurement of strains in elastic rods adjacent to the test specimen. Application of the one-dimensional wave theory to the elastic rods then allows the calculation of the average stress, strain and strain rate of the test specimen at any time.

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DESCRIPTION OF APPARATUS AND TEST PROCEDURE

In order to test at very high rates of loading, a thin specimen of the material is subjected to loading by a strong rectangular stress wave which strains the specimen well into the plastic region. The apparatus employed to test these specimens is a split Hopkinson bar arrangement similar to that used by Chiddister and Malvern (reference 4). Two AISI 4140 steel rods, 0.500 inch in diameter (figure 1) are mounted on six Teflon "V" blocks and are instrumented with three pairs of SR-4 strain gages which are used to observe the incident reflected and transmitted strains. Each pair is diametrically mounted on the pressure bars and connected to opposite arms of a Wheatstone Bridge which produces a voltage proportional to the axial strain. The incident rod, 30 inches in length, has two pairs of gages; the first located 4 inches from the impact end to observe the incident pulse and another pair located 3 inches from the specimen to observe the reflected pulse. A semiconductor strain gage, mounted, 1 inch from the impact end, serves as a trigger for the oscilloscopes which monitor the Wheatstone Bridges. The third pair of gages to observe the transmitted pulse is located 9 inches from the end of the other pressure bar.

The apparatus described above differs from that described in reference 4 by the method of generating the incident pulse. An air gun is employed to accelerate a 10 inch titanium projectile to a final constant velocity determined by the chamber pressure and initial projectile location.

The high pressure chamber of the gun is separated from the barrel by means of a thin plastic diaphragm. The projectile is accelerated to its maximum velocity in the first 60 inches of the barrel when high pressure air ruptures the diaphragm. The remaining 54 inches of the barrel are adequately vented to
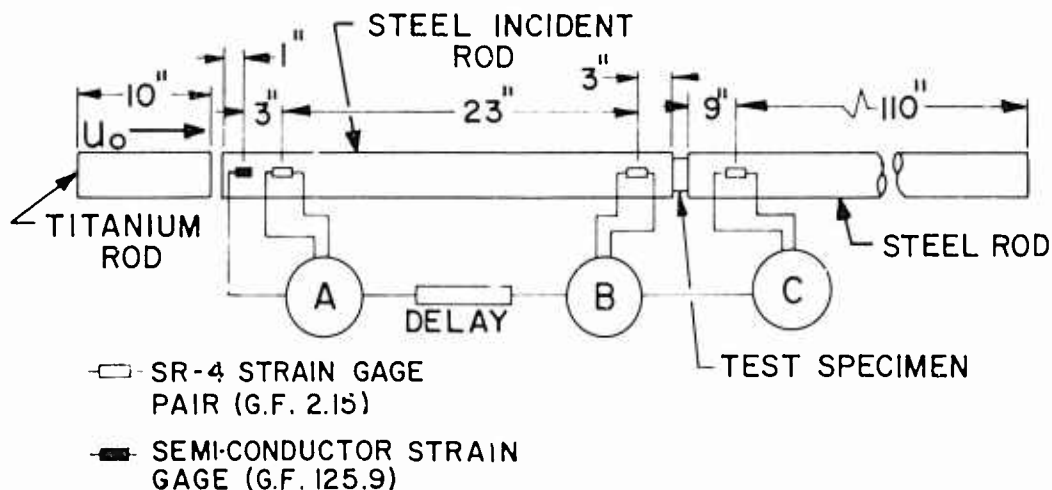

Figure 1 - Split Hopkinson Bar Apparatus

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relieve the driver gas before the projectile passes the velocity measuring section. This section consists of two photoelectric units placed one foot apart, the last station being 2 inches from the barrel end. Each unit is designed to respond when a light beam directed through the barrel is interrupted by the passage of the bore size (.433 inch) projectile. The outputs of these units are used to start and stop an electronic counter.

The projectile generates a 100 microsecond pulse, the time required for an elastic wave to travel from the impact end to the free end of the projectile and return. The pulse length may be varied by changing the projectile length. Titanium has been used because of its low density relative to steel. For this reason, the projectile has a lower impedance than the steel incident rod which insures separation after impact and therefore complete unloading.

The purpose of this test was to determine the effect of rate of strain on the compressive stress-strain relation of pure copper crusher gage material at room temperature. The specimens were all machined directly from crusher gage .325 inch diameter stock. The specimens were machined to lengths of 0.063, 0.125 and 0.250 $\pm$ .002 inch to give a variety of strain rates.

In conducting a test, the two steel pressure bars are carefully aligned and the thin specimen placed between them as shown in figure 1. The two faces of the rods adjacent to the specimen are coated with a thin layer of lubricant. This serves not only to anchor the specimen in place prior to each test, but also acts as a lubricant during the compression of the specimen. It has been stated (reference 3) that the type of lubricant is unimportant; however, the absence of any lubricant results in larger stresses being required to obtain a given strain.

The titanium rod is then propelled by the air gun to the predetermined velocity at which it strikes the impact rod. As the stress-wave strains the semiconductor gage, the signal produced triggers the sweep of the first oscilloscope. The same trigger signal is then delayed 110 microseconds to allow the stress-wave to reach the second set of gages before triggering the remaining oscilloscopes. All preamplifiers are calibrated by insertion of a known resistance into each bridge circuit and blanking the resulting signal every 50 microseconds.

STRESS ANALYSIS

The stress-strain relation of the test specimen may be obtained by applying the one-dimensional theory of reference 1

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to the two pressure bars. This theory in the Lagrangian coordinate system may be written as:

$$\frac{\partial}{\partial t}(u \pm \phi) \mp g \frac{\partial}{\partial a}(u \pm \phi) = 0 \tag{1}$$

where

$$g^2 \equiv \frac{1}{\rho}\frac{d\sigma}{d\epsilon} \tag{2}$$

and

$$d\phi \equiv g\,d\epsilon = \frac{d\sigma}{\rho g} \tag{3}$$

Since the stress levels involved in these experiments are sufficiently below the yield stress, the steel rods may be considered to remain elastic and the above equations become:

$$g^2 = \frac{E}{\rho} \tag{2a}$$

and

$$\phi = g\epsilon = \frac{\sigma}{\rho g} \tag{3a}$$

where E is Young's modulus of the steel rods and ϕ is the "impact velocity."

These equations may be applied to the test specimen by defining the average strain rate in the following manner, figure 2.
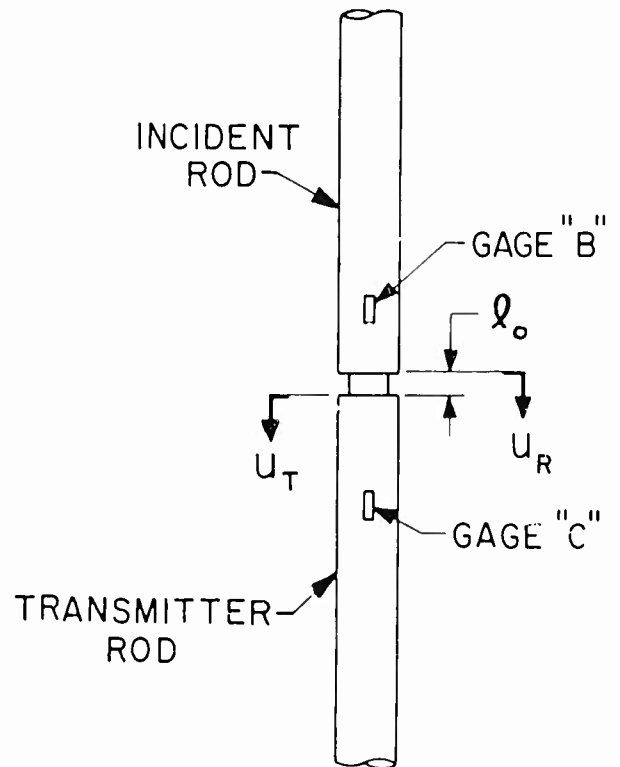
$$\dot{\epsilon}_{AVG} = \frac{u_T - u_R}{\ell_o} \tag{4}$$

Figure 2 - Region Near Test Specimen

INCIDENT ROD

GAGE "B"

ℓ_o

u_T

u_R

GAGE "C"

TRANSMITTER ROD

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In order to determine the velocities u_t and u_r, let us consider the characteristics diagram, figure 3, of that portion of the steel rods adjacent to the specimen. Since the rods are originally at rest and stress free, there exists a region in both rods where $u = 0$ and $\phi = 0$. Equation (1) predicts that along any line of slope "g" emanating from this region, the quantity $(u - \phi)$ is a constant and therefore equal to zero. Since a constant stress pulse is applied in region "I," $u = \phi = \phi_I$. Along any line of slope "-g" emanating from region "I," the quantity $(u + \phi)$ is a constant. Therefore in region "M":

$$U_M + \phi_M = U_I + \phi_I = 2\phi_I \qquad (5)$$

Along any line of slope "g" originating from the reflecting surface R:

$$U_M - \phi_M = U_R - \phi_R \qquad (6)$$

Solving equations (5) and (6) simultaneously yields:

$$U_R = 2\left(\phi_I - \phi_M\right) + \phi_R \qquad (7)$$

Application of equation (1) to region "T" yields:

$$U_T = \phi_T \qquad (8)$$

Therefore

$$\dot{\epsilon}_{AVG} = \frac{\phi_T - \phi_R - 2\left(\phi_I - \phi_M\right)}{l_o} \qquad (4a)$$

If it is assumed that the stress is constant throughout the specimen at any time, then it may be concluded that $\phi_T = \phi_R$. Based on this assumption, it may be seen that the average specimen strain at any time, τ, is given by:
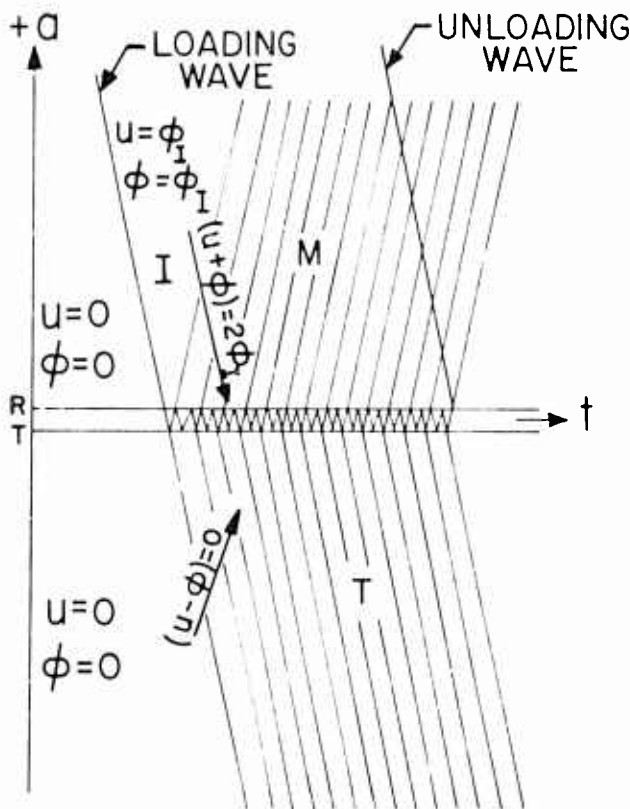

Figure 3 - Characteristic Diagram of Region near Test Specimen

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$$\epsilon_{AVG} = \frac{2g}{\ell_o} \int_0^\tau (\epsilon_M - \epsilon_I)\, dt \qquad (9)$$

Assuming the force to be constant throughout the specimen, we may determine the average engineering stress at any time in the specimen to be:

$$\sigma_{AVG} = \left(\frac{A_T}{A_o}\right) E\, \epsilon_T \qquad (10)$$

where A_o is the initial cross-sectional area of the specimen. These results are in agreement with the results obtained by both Hauser, Simmons and Dorn (reference 5) and Chiddister and Malvern (reference 4) if it is assumed that the measured strain is the same as the strain at the reflecting surface. This is not a valid assumption in this case due to the finite time required to reach the initially constant incident stress level. It should be noted that the incident pulse no longer has the rapid rise time upon reflection as seen in figure 4.

In order to demonstrate the method of obtaining the strains needed to integrate equation (9), an example of the output from gages "A", "B" and "C" for a typical test is presented in figure 4. When made time coincident, the
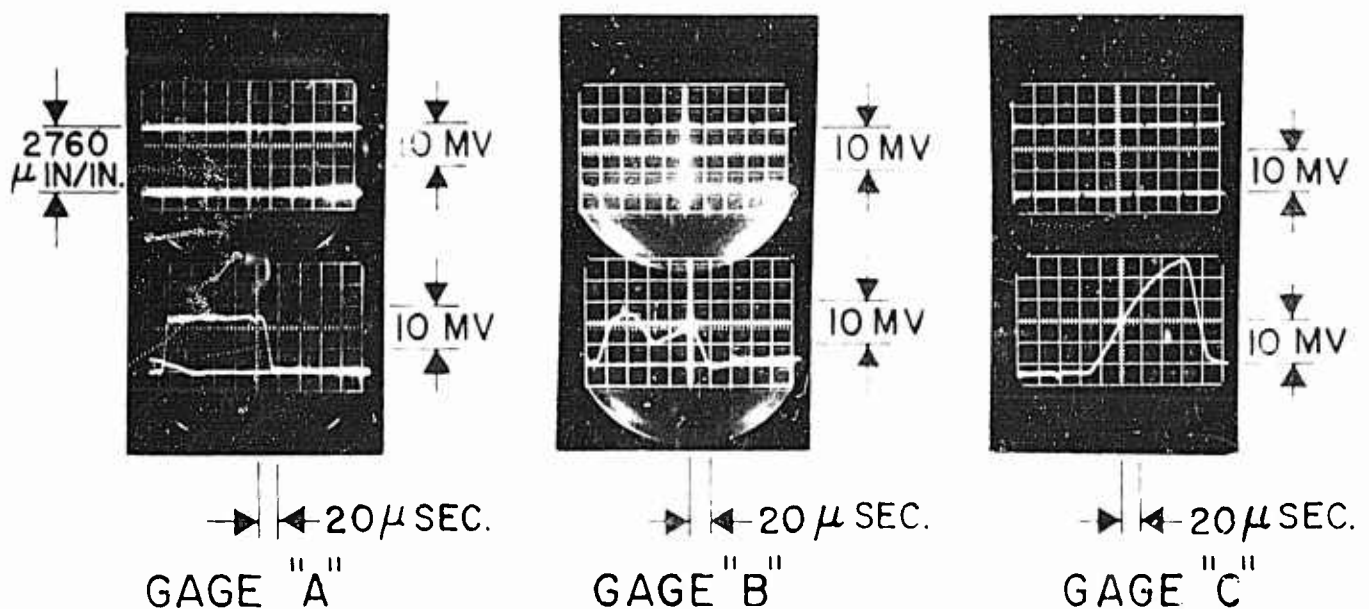

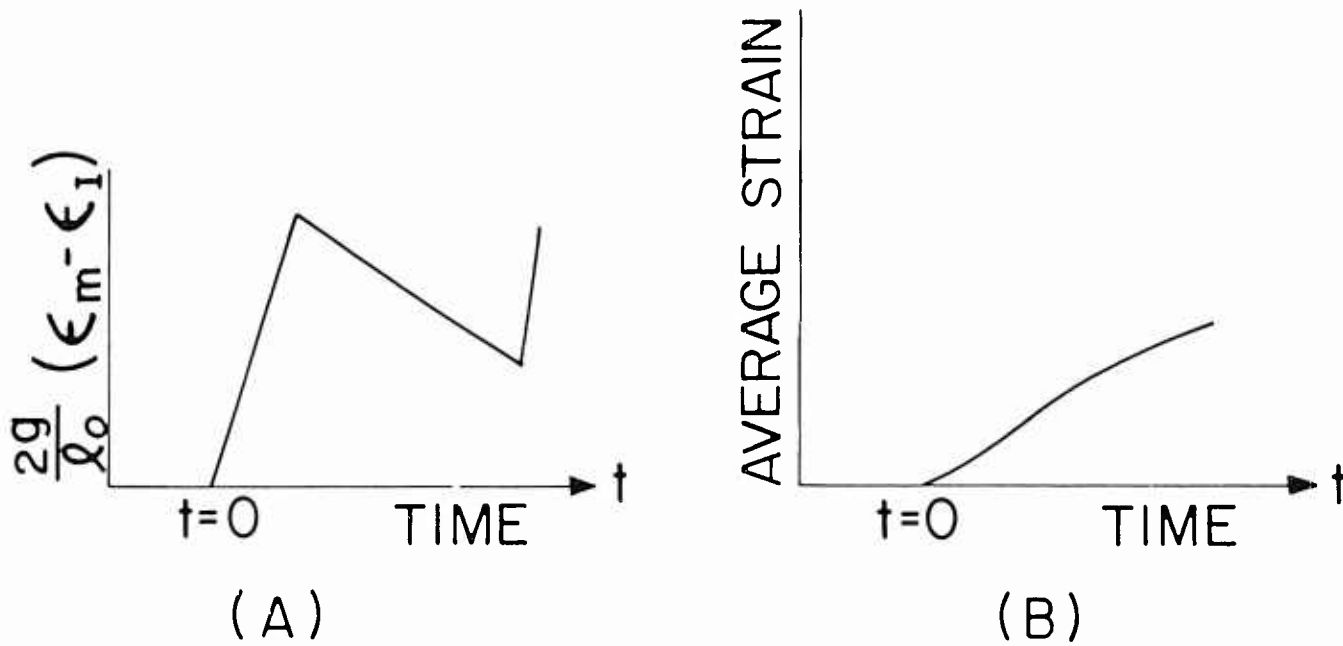Figure 4 - Typical Output for 1/16" Crusher Gage Specimens

Figure 5 - Example of Strain Analysis

difference between the outputs of gages "A" and "B" is the integrand of equations (9) and is presented in figure 5a. Graphical integration of figure 5a when multiplied by the constant $2g/\ell_o$ yields the average specimen strain as a function of time as shown in figure 5b.

As mentioned previously, the average specimen stress may be obtained directly from the record of transmitted strain. Using time as the parameter, the average engineering stress of the specimen may be obtained as a function of strain for a single test as shown in figure 6.

RESULTS AND DISCUSSION

The results of each test could be presented in the same form as figure 6. However, it can be seen that the strain rate varies continuously during each test. In order to determine the dependence of the stress on strain rate, the same information is presented in figure 7 for constant values of strain. Since the lines of constant
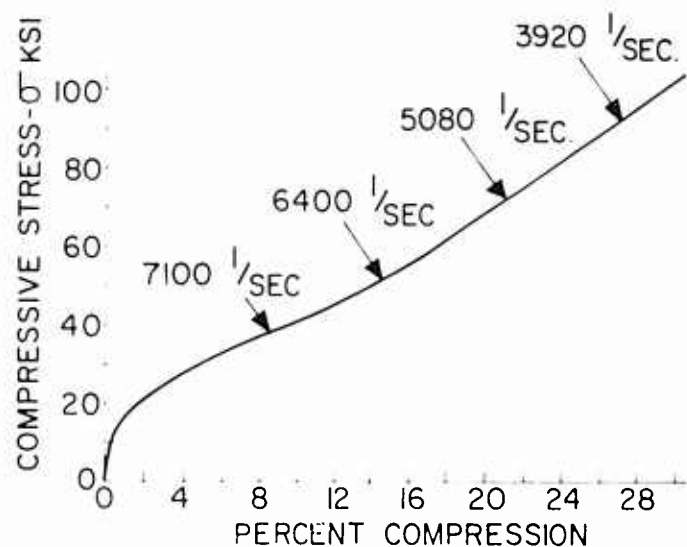

Figure 6 - Stress-Strain Results For a Single Test

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strain are nearly vertical, this
type of material is considered
only slightly strain rate
sensitive. The violent scatter
of data at the higher rates of
strain is such that no con-
clusion may be drawn as to the
stress-strain relation in this
region. These high rates of
strain were obtained with
extremely thin specimens
where the stress may no longer
be uniaxial. A similar
phenomenon was observed in
aluminum (reference 5) and
the authors concluded the
existence of a limiting
strain rate for that material.

Employing figure 7, the
engineering stress-strain
relation may be obtained for
a constant strain rate and is
presented in figure 8. This
manner of data reduction is
only valid if the stress may
be expressed as a function of
the instantaneous values of

Figure 7 - Effect of Strain
Rate on Stress

strain and strain-rate. No attempt has been made to determine
the effect of the loading history of the specimen on these
data. The quasi-static data was obtained at a strain rate
of 1.66×10^{-3} in/in/sec on a standard Southwark Universal
testing machine. It may be seen in figure 7 that this
material obeys the generalized stress-strain relation
suggested by Lubliner (reference 7) which is of the form:

$$\frac{\partial \epsilon}{\partial t} = f(\sigma, \epsilon)\frac{\partial \sigma}{\partial t} + g(\sigma, \epsilon)$$

The slope of the stress-strain relation in the plastic region
is apparently independent of these rates of strain. This
observation tends to support the experimental results of Bell
(reference 8) on annealed copper.

Crusher gages employ very pure annealed copper spheres
or cylinders to determine pressure. These gages are calibrated
statically and used where more fragile devices would fail. A
typical use of these gages is in the high-pressure chamber of
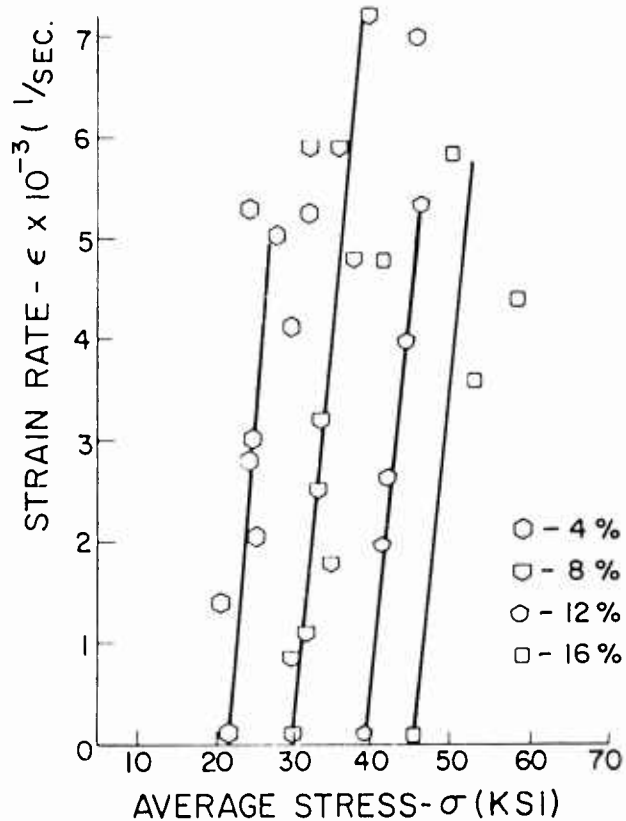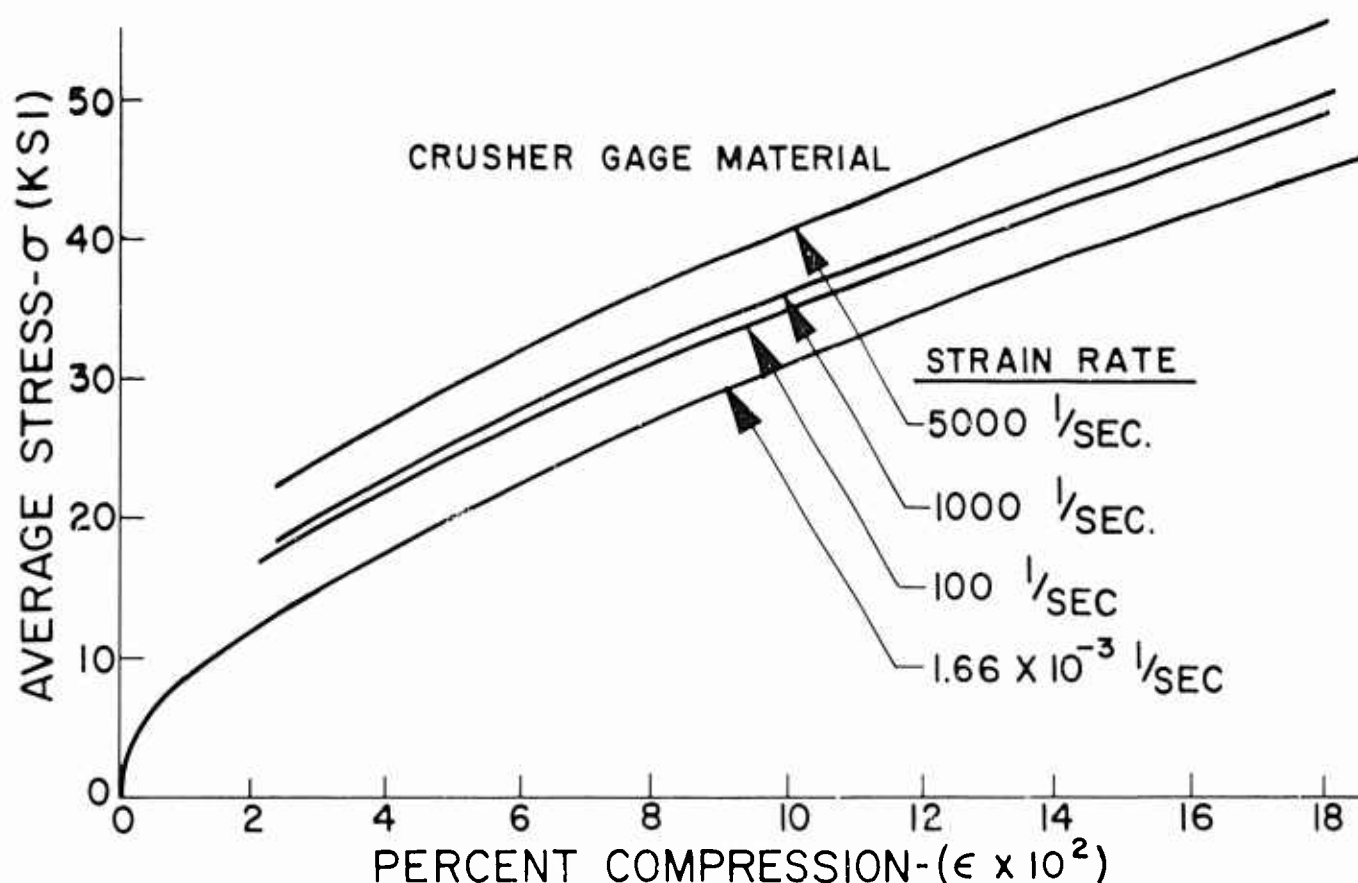high performance guns where the gage is subjected to violent

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Figure 8 - Dynamic Properties of Copper
Crushed Gage Material

changes of pressure. However, for a gage that employs a
.500 inch copper cylinder, the maximum strain rates observed
were on the order of 100 in/in/sec. Therefore, the permanent
strain due to peak chamber pressures will have a maximum
error of approximately two percent strain due to strain rate
sensitivity. Since the dynamic stress-strain curves are
roughly parallel with constant slopes (figure 8), the percent
error becomes small as the maximum strain becomes large.

CONCLUSIONS

Dynamic stress-strain relations have been obtained for
copper crusher gage material at rates of strain from
1.66 x 10^{-3} in/in/sec to 7.15 x 10^{3} in/in/sec with the
following results:

a. Annealed copper crusher gage material is strain-rate
dependent as shown in figure 8.

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b. This material appears to obey the generalized stress-strain relation suggested by Lubliner.

c. A static stress-strain relation may be used satisfactorily to predict plastic wave propagation speeds for a given value of strain.

d. Static calibration of crusher gages will introduce an insignificant error due to strain rate sensitivity in measuring the peak pressures of high performance guns if the gage is selected such that large strains are measured at rates below 100 in/in/sec.

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